This research program was stimulated by research results in other areas; we hope that our results will stimulate research in still other areas. Surely the product will exceed the sum of the parts.

LITERATURE CITED

(1) Colman, E. A. Operation Wet-Blanket: Proposed research in snowpack management in California. Paper presented at Pacific Southwest Regional Meeting. Amer. Geophys. Union, Berkeley, California, Feb. 5, 1955. 10 pp illus., Proc.

(2) Richards, L. G. Progress Report, Inventory of Sierra Hydrologic Characteristics. California Forest and Range Exp. Sta., Berkeley, Calif., 5 pp Proc., 1957.

(3) Anderson, H. W. and Pagenhart, T. H. Snow on Forested Slopes. 25th Ann. Western Snow Conf. Proc. pp 19-23, 1957.

(4) Court, Arnold. Wind Direction During Snowfall at Central Sierra Snow Laboratory. 25th Ann. Western Snow Conf. Proc. pp 39-43, 1957.

(5) Nelson, R. E. Soil-Vegetation Survey of a Central Sierra Snow Zone Watershed. Calif. Forest and Range Exp. Sta. Misc. Paper 21, 43 pp illus., Dec. 1957.

(6) Walsh, K. J. New Meteorological and Snow Studies in the Central Sierra. 25th Ann. Western Snow Conf. Proc. pp 43-45, 1957.

(7) Wyckoff, P. J. Snow Surveys from the Snow Surveyor's Side. 25th Ann. Western Snow Conf. Proc. pp 57-59, 1957.

FOREST SHADE RELATED TO SNOW ACCUMULATION[1]

H. W. Anderson, R. M. Rice, and A. J. West[2]

INTRODUCTION

One of the better ways to start an argument is to make any categorical statement on how forests affect snow and the yield of water from snow. Forests intercept snow; therefore they must reduce the snow pack. Forests shade the snow; therefore they prevent melting and reduce evaporation, causing the snowpack to increase. Forest trees radiate heat and use water; therefore they decrease the snowpack. And so it goes, each effect of the forest has its conflicting effect; each refinement of measurement of the forest demonstrates its own inadequacy and points to the need for further refinements.

This paper is a report of our progress along this path--from measurement of forest effects on snow to refinement of measurements to recognition of still other effects. The study is one of the first steps in our program aimed at developing and testing ways of cutting forests and treating other lands to improve water yield from the snow zone.

We are currently trying to develop a system of physical measurements of forests that will more adequately index the various effects that forests have on snow. To do this, we have tested various measurements of the forest against the snow accumulation and melt at individual points within snow courses. The measures tested range from a single-valued index of forest cover to a 7-variable expression of the same forest cover.

We have made the studies in 3 parts: (1) A study of the effects on snow of the conventional forest variables of hemispherical cover and cover density, (2) a study of the effects on snow of forest variables when the hemispherical cover was differentiated into shade cast by the trees to the south and shielding or radiation produced by the trees to the north, and (3) a study of the effects on snow of several physical indexes of the forest. These studies are frankly exploratory; yet the results are interpreted as the best knowledge we have to date.

---

[1] The study is part of the Cooperative Snow Management Research program being conducted by the California Forest and Range Experiment Station, with the cooperation of the California State Department of Water Resources.

[2] Snow Research Leader and Research Foresters, respectively, California Forest and Range Experiment Station, U. S. Forest Service, Berkeley, California.

HEMISPHERICAL COVER AND COVER DENSITY EFFECTS

For the first part of the studies we asked the questions: Were some of the poor results previously reported on the relation of forests to snow the result of crude maps (1, 2)? Are hemispherical cover and cover density as poor indexes of the effects of forests as had been reported? We made better maps and further analyses to see.

METHODS

We related forest conditions to: (1) maximum accumulation of the winter snowpack, expressed as the April 1 water equivalent, and (2) spring melt rate, expressed as the ablation of the snowpack water equivalent after April 1, in inches per degree-day of air temperature greater than 35°F. (3, 4) Forest conditions were expressed by simple two-variable indexes, the conventional ones of hemispherical cover and cover density.

The snowpack data used in the study were collected at the Central Sierra Snow Laboratory as a part of the Cooperative Snow Investigations of the Corps of Engineers and the Weather Bureau. The data analyzed were obtained from an average of six snow measurement points in each of five snow courses during a period of three years (1949-1951). All five snow courses were in the red fir forest type. The points in each course were selected so as to have a wide range in amount of forest cover. The points selected for analysis in a typical snow course are shown in figure 1 (5).

The maps are obviously pretty crude. Trees were characterized at the margin of the openings - taller trees behind these had been ignored. Consequently, in 1956 we remeasured the forest cover around each point in each course, using a transit and chain. Our method was to set up over each sample point and plot on polar coordinate paper the angle to the base of the trees, to the top of the trees, and to the horizon when visible. The hemisphere was divided into parts by 15 degrees of azimuth and 10 degrees of vertical angles. At each intercept of azimuth and vertical angle we recorded the distance to the trees, the distance through the foliage to the open air, and the cover density.

Then we determined hemispherical cover (Hc), the portion of the sky screened by tree canopy, and the cover density (C), the average density of the tree canopy. We tested the relation of these variables to April 1 snow pack and melt rate after April 1 by covariance analysis.

RESULTS

The results are shown by the regression equation, analyses 1-3 in Table 1. We must conclude that the indexes were poor. At best, only 3 percent of the variation in the April 1 snow pack (Sn) was explained by the hemispherical cover (Hc) and cover density (C). The variables explained 27 percent of the variation in spring melt (Ab). In spring melt, the hemispherical cover was significant at the 1 percent level. In neither April 1 snow accumulation nor the spring melt, did cover density, C, approach significance. This failure of cover density to be significant in this and subsequent analyses may be explained by the effects of cover on visible and infra-red radiation. We will discuss this later.

FOREST SHADE AND SHIELDING EFFECTS

Secondly, we asked: does hemispherical cover fail as an index of snow accumulation and melt because these are conflicting effects between trees to the north and trees to the south? We separated the canopy and tested the relation to snow accumulation and melt at the same 5 snow courses, using 5 points in each course.

METHODS

The forest around each point in a snow course was divided into 2 parts. The half to the south was indexed by the shade produced (Sh). The shade was expressed as the duration of shade during the period April 1 to June 15, weighted by the solar energy (3). The forest to the north was indexed simply as the average ratio of the height of the trees at the forest margin to the distance from the sampling point (h/d).

The relation of April 1 snow pack (Sn) and melt rate after April 1 (Ab) to forest Shade (Sh) and forest heights to the north (h/d) was determined as the within-course regression of an analysis of covariance.

Table 1.--Regression results, effect of hemispherical cover (Ch), and cover density (C), on April 1 snow pack (Sn) and spring melt rate (Ab), Central Sierra Snow Laboratory, 1949-51

Item	Dependent Variable	Forest Variable Effect1/			Regression Equation Constant	Explained Variance
		Ch	Ch^2	C		
Units	2/	Pct/100	Pct^2/100	Pct/100		
Range	2/	.34-.92	12-85	.60-.89		
Analysis 1	Sn	69	-70	-	15.4	.033
Analysis 2	Ab	-.082	-	.035	.131	.267

1/ "Effects" are the change in April 1 snow pack (Analysis 1) or ablation of pack after April 1, (Analysis 2) associated with a change in each forest variable over its range in the data. For example, the melt rate (Ab) decreases .082 inches per day with Ch = 92 percent versus Ch = 34 percent. range .20 to .82

2/ For Sn, units are inches water equivalent/; for Ab, units are inches per degree day greater than 35°F, range .06 to .29.

Table 2.--Regression Results, Effects on Snow Increments, Central Sierra Snow Laboratory, 1947 - 1950 1/

Item	Forest Variables2/					Joint Variables2/			Meteorological Variables2/						Energy Variables2/		Regression Equa. Const.	Explained Variation
	Cv	Dp	Hc	Hc^2	S	HcWec	W/S	CdE	W	Wec	Wec^2	Snc	Cl	Cd	E	En		
Units	pct/100	feet	pct/100	pct/100	pct/100	in./day	mph	pct/100	mph	in./day	$(in.)^2/(day)^2$	in.	pct/100	pct/100	pct/100	pct		pct
Max. Value	.767	17.1	.64	.410	.71	.311	33.12	.271	8.00	.714	.509	30.0	.72	.554	.484	1561.5		
Min. Value	.013	0	.29	.086	.24	.011	3.84	.021	2.74	.038	.001	-23.1	.17	.157	.202	161.5		
Range	.754	17.1	.35	.324	.47	.300	29.28	.250	5.26	.676	.508	53.1	.55	.397	.282	1400.0		
	---Percent change in water equivalent, and probability of chance effect---																	
Analysis 1 3/	10	6	-7	-	-	-	-	-	-	-	-	341	26	-	-	5	.603	88
Probability 4/	7.1	38.2	3.2									<.1	<1			13.4		<1
	---Gain or loss in snowpack in inches of water equivalent per day, and probability of chance effect-----																	
Analysis 2 3/	.049	.058	.472	-.596	-.012	-.006	.088	-.418	-.055	.460	.121	-	-	.431	.156	-	-.500	88
Probability 4/	11.0	24.5	5.5	2.5	87.5	94.5	50.5	3.4	55.0	1.2	27.5			<1	<.1			<1
Analysis 3	.037	.064	.685	-.526	-	-	-	-.543	-	.536	-	-	-	.537	.177	-	-.505	88
Probability 4/	19.5	17.5	11.2	4.0				<.1		<1				<1	0.9			<1

1/ "Effects" are the change in snowpack water equivalent, Sni, (Analysis 1) or daily increment to snowpack, Wei, (Analyses 2 and 3) associated with a change in each variable over its range in the data, other variables being held constant. For example, change in Cv over its range of 1.3 to 76.7 percent would change snow accumulation 10 percent in Analysis 1, or rate of increment to snowpack by 0.049 inches/day in Analysis 2.

2/ For definition of variables, see text.

3/ Analysis 1 used log transformations; analysis 2 and 3 were arithmetic.

4/ The figure given is the probability (as a percent) that the effect shown could be due to a chance correlation.

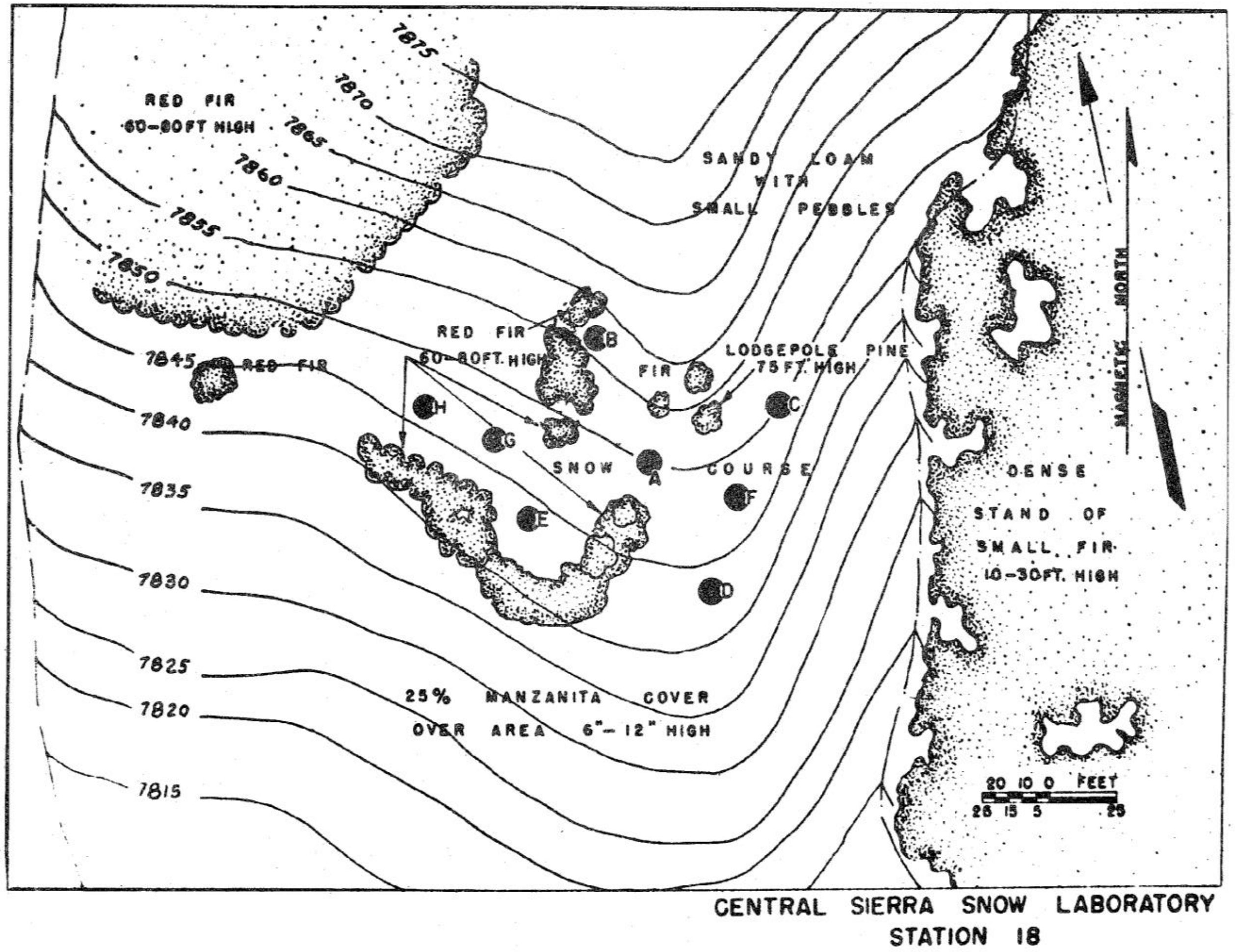

Figure 1.--Map of typical snow course, Snow Course 18, Central Sierra Snow Laboratory, 1951 (5).

RESULTS

The change in April 1 snow pack with shade and trees to the north (h/d) is shown in figure 2, together with the regression equation defining that relationship. Both shade and trees to the north were significant at the 1 percent level. The relation of April 1 snow pack to shade was curved. The maximum pack was obtained where shade was 65 percent, the snow pack decreasing with shade greater than 65 percent. On the average, the April 1 snow pack was 11 inches less in a dense forest than in large open areas. Field observations (3) indicate that in the Sierra this difference is the net effect of differences in winter melt, loss by interception and evaporation, and blowing of snow. These differences are, of course, imperfectly indexed by the shade and h/d variable; in fact, only 56 percent of the variation was explained by these two variables. The results say that shade throughout its range was twice as effective in increasing April 1 snow pack as trees to the north were in reducing the pack. There is no question that these variables, though imperfect, are better than conventional hemispherical cover and cover density.

The change in the rate of melt of the snow pack after April 1 with shade and h/d is shown in figure 3, together with the regression equation. The shade variable was significant at the 1 percent level; the h/d variable at the 5 percent level. Melt rate decreased progressively with shade and h/d, but again curvilinearily with shade: 65 percent shade was 88 percent as effective as full shade in reducing snow melt. The trees to the north were only 12 percent as effective as the shade from trees to the south in reducing the melt of the snow pack. Coincidentally, sky radiation is about the same proportion of direct solar radiation. Together, the two forest variables explained 40 percent of the variance of the melt rate between points in a snow course.

APPLICATIONS

What forest cutting will give the most snow pack? The results of this study says, "It depends on when you want the water." We can calculate the effects of cutting forests in strips of various widths. Such calculations for east-west oriented strips are shown in figure 4. On April 1 the maximum snow pack would be obtained from strips cut about equal to the height of the trees. This width is consistent with reports of other studies (6, 7). However, snow melt after April 1 would be more rapid in wide than in narrow strips; so as the spring season progresses, the maximum unmelted snow would be found in narrower and narrower strips. By June 9, in the average year, the maximum snow water equivalent would be found in strips half as wide as tree heights.

The calculated timing and amounts of snow water delivery for 3 conditions is shown in figure 5: a pack in a large unshaded area, a pack in a dense forest, and a pack within an east-west cut strip half as wide as the heights of the adjacent trees. On April 1, the snow pack water equivalent in the cut strip and in the unshaded area are nearly identical, the pack in the dense forest contains 11 inches less water. On June 9, when all snow is gone from the unshaded area, 16 inches water equivalent remains in the dense forest, and 20 inches in the cut strip. The last snow disappears from the dense forest and the cut strip at about the same time, 16 days later.

FOREST AND CLIMATIC EFFECT

Finally, we asked: How does snow accumulate? Does the forest affect increments of snow during the accumulation period? How are the increments to the pack affected by direct solar radiation received, by clouds, by wind, by interception, by amount of snow outside the forest? We tested variables intended to index each of these parts of the environment and their effects on snow accumulation.

METHODS

We analyzed nine winter increments to the snow pack at five points in five snow courses, together with three May depletions of the pack. The data were for 1- to 5-week periods, spread over the three years 1947-1950. The five snow courses (3) had been selected so that a wide variation would be found in the forest cover at the individual points in each course. The points selected for analysis had wide differences in forest cover.

Increments and depletion of the snow pack were related to several variables of the forest canopy and to control variables by multiple regression analysis. The control variables were included to index the gross differences in the amount of snowfall, solar energy, and wind between periods. The forest cover variables were selected to index specific variations they brought about in each climatic effect at each point.

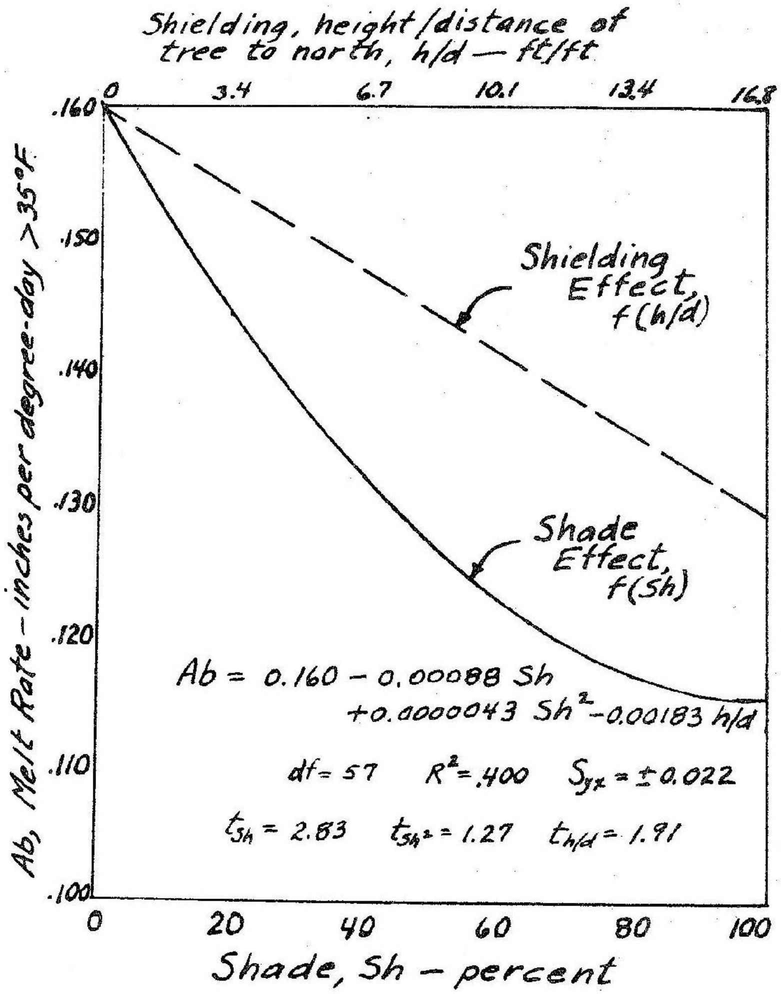

Figure 3.--Change in melt rate after April 1 (Ab), with shade from trees to the south (Sh) and height to distance ratio (h/d) of trees to the north of a point (3).

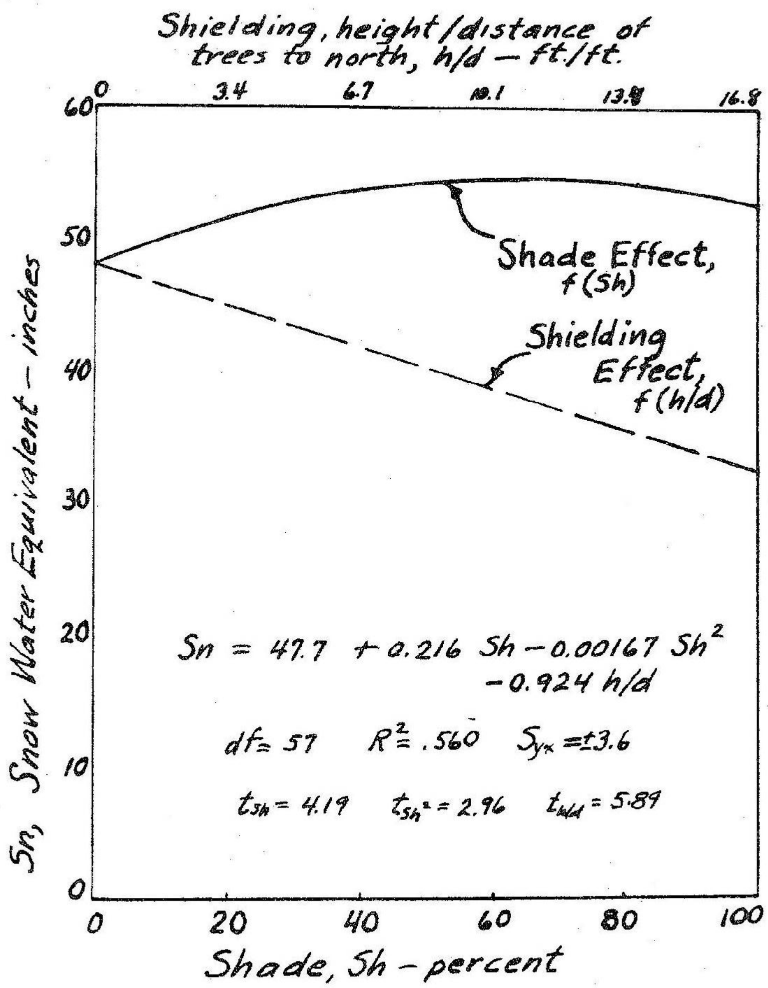

Figure 2.--Change in April 1 snow pack water equivalent (Sn), with shade from trees to the south (Sh) and height to distance ratio (h/d) of trees to the north of a point (3).

Climatic controls were of two kinds, snow course and meteorological measurements. The increment of snow at a snow course indexed the amount of precipitation and the general heat balance for a period. Course No. 3 (5) was chosen for this control because it was relatively free of any local forest influence. The meteorological measurements were solar energy, clouds, and wind. These measurements were used to index any additional effects of the climate not included in the snow course control, principally, differences between climatic effects on the open control course and the "forest influenced" other courses.

The forest variables were aimed at indexing the forest effects on snow reaching the ground, redistribution of snow, and melt. Interception of direct solar radiation by the forest canopy was indexed by the cover density and depth. To obtain one index, the cover density in the solar path during a period of snow increment was weighted by the energy received each hour of the day in that path. Tabulations of solar intensity received on any slope, made by our Fire Research Division, facilitated these weightings. To index the effects of multiple reflections within the canopy in retarding penetration (8), we used the depth of the canopy, again weighted by the solar energy for each hour in the solar path. Depth would be particularly important for the infra-red radiation, which is highly reflected by forest vegetation and so may bounce through thin vegetation which appears dense to ordinary visible light. What we see and what a camera sees is not what the snow sees. Compare the ordinary and infra-red photos of figure 6. The infra-red radiation is penetrating the canopy and brightly reflecting from the foliage.

To index the long-wave radiation balance between forests, snow, and sky we chose the hemispherical cover, weighted by the cover density. This is the proportion of the sky obscured by the trees. In addition, the interception of snow was indexed by the hemispherical cover times the amount of snowfall at the control snow course. It is obvious that hemispherical cover should also influence wind scour, melt, and evaporation. To index the net effects of wind, we used the "hemispherical cover" in the SW and NE octants, called the "Shelter", weighted by the total wind passage during the period. Analyses by Court (9) have shown that most of the winds during snow storms and most of the warm afternoon winds between storms are from the southwest.

VARIABLES AND DEFINITION

Sni, Snow Increment (the dependent variable in analysis #1, Table 2), is the change in the water equivalent at a snow sampling point during a period, (range -23.0 to 37.5), inches.

Wei, Snow Increment Rate (the dependent variable in analyses #2 and #3, Table 2), is the rate of change of water equivalent at a snow sampling point in a period, (range -0.262 to 0.893), inches per day.

Cv, Weighted Cover Density, is the cover density along the sun's path, weighted by the proportion of solar energy coming from various segments of the path, percent.

Dp, Weighted Cover Depth, is the distance through the crown that solar radiation travelled to reach the sample point, weighted by an index of the proportion of solar energy transmitted by the crown (that is the energy times 100 minus the cover density), feet.

Hc, Hemispherical Cover, is the proportion of the sky obscured by trees or topography—the sine of the vertical angles above the horizon times the cover densities, percent.

S, Shelter, is the hemispherical cover in the SW and NE octants, percent.

Wec, Major Climatic Control, is the mean rate of change of water equivalent of a level exposed snow course (CSSL No. 3 (5)), inches per day.

HcWec, Index of Interception Loss, is the product of the hemispherical cover and the rate of snow accumulation at the control, inches per day.

W, Wind, is the mean wind velocity in the period at an anemometer 18 feet above the surface in the vicinity of the control snow course, miles per hour.

Snc, Snow at Control, is the mean change in water equivalent during a period at a level exposed snow course (CSSL No. 3 (5)), inches.

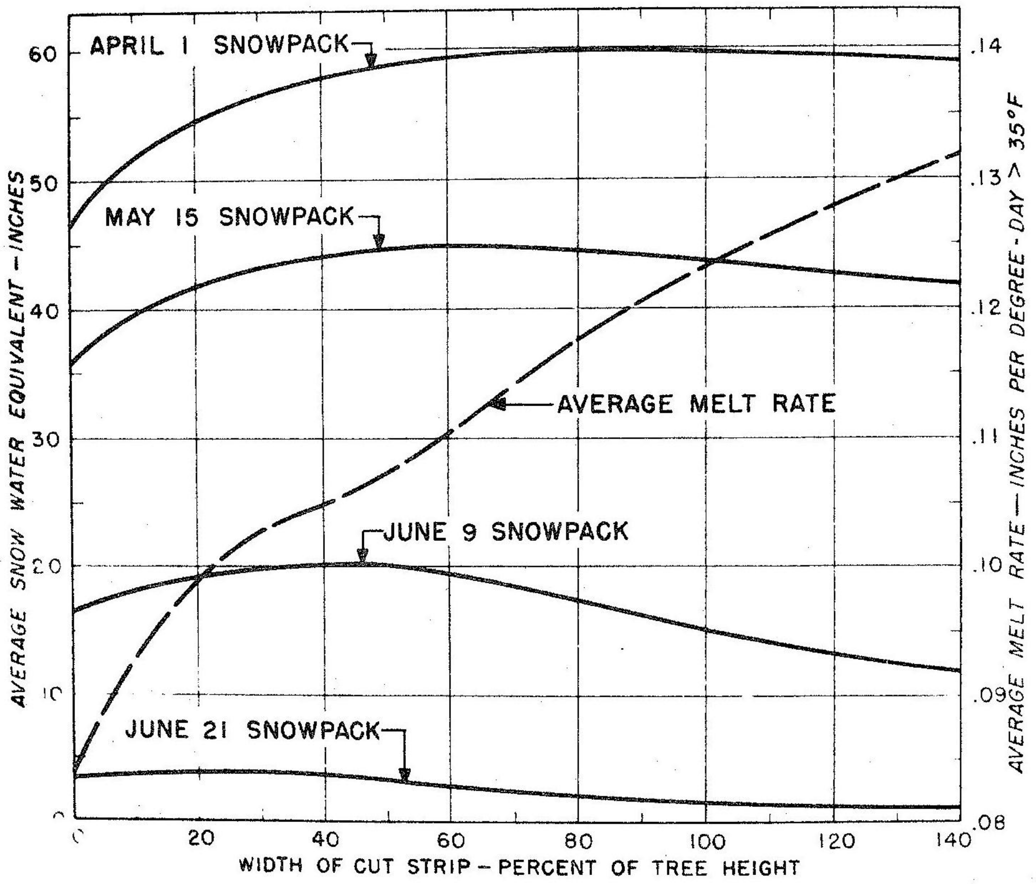

Figure 4.--Snow pack water equivalent on various dates in an average year within strips of various widths cut in a forest.

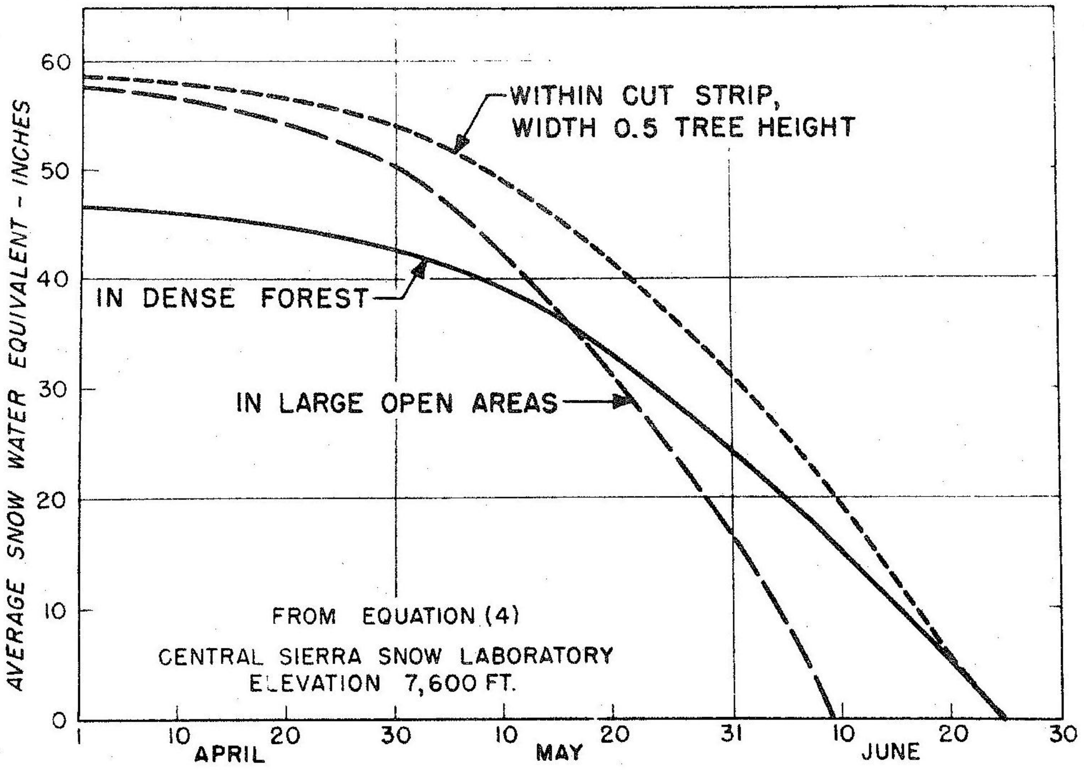

Figure 5.--Snow pack water equivalent at various dates in an average year for two forest conditions and in the open.

Cl, Clouds, is the average cover of low and middle clouds in a study period, neglecting cirrus clouds, percent.

Cd, Cloudiness, is a measure of the cloud cover in a study period weighted by the degree to which they reduced radiation passing through them (10), percent.

E, Available Energy, is the proportion of the solar constant that would impinge on an exposed slope similar to the sampling point during a period, percent.

CdE, Transmission through Clouds, is an index of the proportion of the available energy that is transmitted through the clouds to the earth's surface - the product of Cd times E, percent.

En, Accumulated Energy, is the summation of the solar energy (E x time) for a period, cumulative percent.

ANALYSES

Once the variables were chosen, defined, and the data for the 12 periods assembled, we were ready to choose the analysis models. We considered two possibilities: (1) assuming that the effects of the variables were proportional and could be represented by simple logarithmic transformations, and (2) assuming that the effects were for the most part additive and linear and that any curvilinearity and joint effects could be represented by quadratic and product terms. In practice we tested both assumptions, using multiple regression analyses.

RESULTS

The results are summarized in Table 2. Analysis No. 1 gives the results when a logarithmic transformation was made on the data. In this analysis snow increments and melt in periods were related to three forest variables and three climatic controls. In analysis No. 2 the rate of snow water increments in the nine winter accumulation periods only were related (non-log) to 7 forest variables and to 6 climatic controls. In analysis 3, we dropped from analysis 2 those variables which apparently had little physical significance, leaving 4 forest variables and 4 climatic control variables.

The results are shown as the individual effect of each variable on snow increments for a variation of the variable throughout its range in our data. The effect on total snow water equivalent is given in analysis 1, and the effects on average daily increment of snow water equivalent are given in analyses 2 and 3. The probability of the effect being due to chance alone is given below each indicated effect, 5.0 would be the 5 percent level, and so forth.

Effects of Forest on Snow

The results of Analysis No. 1, Table 2, indicated that the snow increased with two forest variables and decreased with another. Snow was increased 6 to 10 percent by the interception of solar energy as indexed by the cover density and depth in the solar path. Snow was decreased 7 percent by the general hemispherical cover, indexing radiation melt and interception of snowfall. We can conclude that to the extent that forests can be cut so as to leave the trees to the south and remove the trees to the north of and over a point, snow can be increased.

The results of Analysis No. 2, Table 2, indicated that sizeable increases of snow in the winter were associated with several of the forest variables. Again snow increased with the index of intercepted solar radiation, the increases amounting to 0.049 to 0.058 inches of water per day. These increases could be important over a whole season. The general hemispherical cover had a definite curvilinear effect, with snow increasing for small amounts of hemispherical cover (to 33 percent) and decreasing for greater cover. The decrease from this maximum is 0.16 inches of water per day. Our index of the snow interception loss (HcWec) had a high probable error, yet it gives the right order of magnitude for interception loss (-0.07 Wec). Shelter from the wind seemed to have little effect as we indexed it. In larger scale tests, shelter from wind has been found important (11). We do not intend to abandon our attempts to index these physical effects.

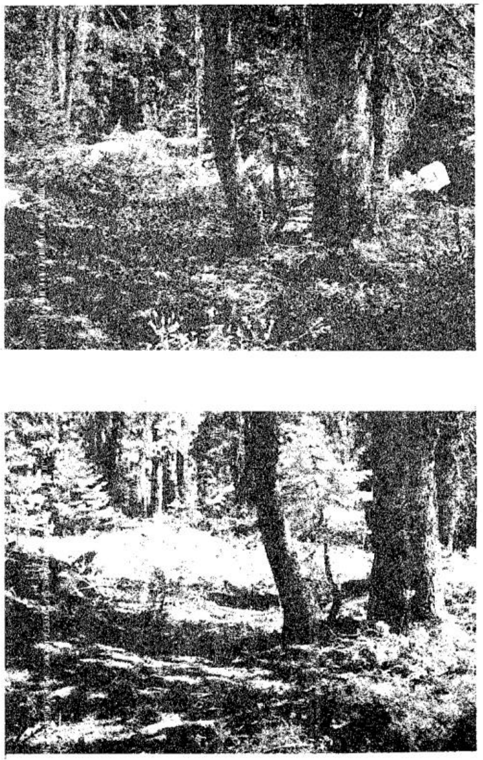

Figure 6.--Forest canopy as recorded with ordinary panchromatic film (upper) and infra-red film (lower) CSSL Snow Course 19, Point E, (5) Azimuth 30°, 10:30 a.m. August 23, 1956.

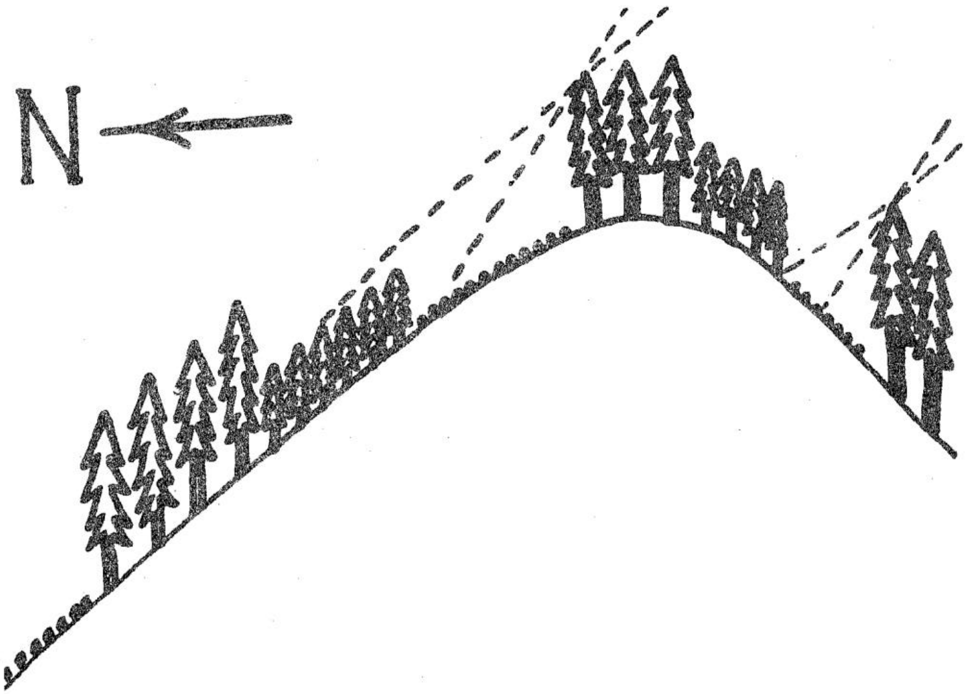

Figure 7.--"Ideal forest", a wall-and-step forest, resulting from strip cutting, with direction of strips normal to direction of maximum solar radiation, wider strips on north than on south slopes.

Rather, we will try to improve and purify the variables indexing the effects. To this end we are measuring snow at 63 new snow courses, 24 points per course.[3/]

The results of Analysis No. 3, Table 2, are similar to those of Analysis No. 2. When the variables of little effect were dropped out, the explained variance still remained the same, 88 percent. In this and other analyses, the regression coefficients of the equations can be obtained by dividing the effect shown in Table 2 by the range in the variable. The constant in such a regression equation is also given in the Table.

Effects of the Climatic Control on Snow

The climatic variables were included primarily to minimize masking effects of climate on the forest variables. However, some of the results of relating snow melt to these climatic variables are informative. The clouds were highly important in influencing increments to the snow pack. Snow increments at courses with forests increased with cloudiness in all periods and sites, but the increase was somewhat less for periods with high cloudiness and high energy.

APPLICATION OF RESULTS

Throughout all of this testing of variables we have kept in the back of our minds a vision of the "ideal forest"--one managed for water production. Judging from these analyses, the "ideal forest" would result from strip cutting. The strips would be oriented across slopes perpendicular to the hour angles with maximum solar energy; generally the strips would be east-west on north and south slopes, NE-SW on east slopes, and NW-SE on west slopes. Successive cuttings would proceed generally southward, that is, toward the maximum radiation. Once through a cutting rotation we would have established a wall-and-step forest as shown in figure 7. This forest would provide the maximum shade with the minimum interception and back radiation. The width of the cutting would be governed by the aim in water production--wider strips for maximum total water yield, narrower strips for maximum delay of snow melt. For the same delay in melt, wider strips could be cut on north slopes than on south.

The described "ideal forest" is a first crude approximation, obviously oversimplified. None-the-less its definition is one more step toward the day when the snow zones of the West are managed for water, not timber alone.

LITERATURE CITED

(1) Corps of Engineers, Snow Investigations. Radiation in forest at Willamette Basin Snow Laboratory. Research Note 12, 17 pp, Proc., 1953.
(2) Mixsell, J. W., D. H. Miller, S. E. Rantz, and K. G. Brecheen. Influence of terrain characteristics on snow pack water equivalent. Research Note 2, Coop. Snow Investig. So. Pac. Div. Corps of Engr., U. S. Army, San Francisco, pp. 1-9, Proc., 1951.
(3) Anderson, H. W. Forest-cover effects on snow pack accumulation and melt, Central Sierra Snow Laboratory. Trans. Amer. Geophys. Union 37, pp. 307-312, 1956.
(4) Church, J. E. The melting of snow. Proc. Central Snow Conf. 1, pp. 21-32, 1941.
(5) Corps of Engineers-Weather Bureau. Hydrometeorological log of the Central Sierra Snow Laboratory, 1950-51. Coop. Snow Investig. Publ. pp. 14-72, 1952.
(6) Church, J. E. The conservation of snow; its dependence on forests and mountains. Sci. Amer. Sup. 74, pp. 145, 152-55, 1912.
(7) Kittredge, Joseph. Influence of forests on snow in the ponderosa-sugar pine-fir zone of the Central Sierra Nevada. Hilgardia 22, pp. 1-96, 1953.
(8) Miller, D. H. Snow cover and climate in the Sierra Nevada, California. Univ. Calif. Publ. Geog., 11, pp. 1-218, 1955.
(9) Court, Arnold. Wind direction during snowfall at Central Sierra Snow Laboratory. 25th Ann. Western Snow Conf. Proc. pp. 39-43, 1957.
(10) Haurwitz, Bernard. Insolation in relation to cloud type. Jour. Meteorol. 5(3), pp. 110-113, 1948.
(11) Anderson, H. W. and T. H. Pagenhart. Snow on forested slopes. 25th Ann. Western Snow Conf. Proc. pp. 19-23, 1957.

[3/] See "Progress in Snow Management Research in California" in this Proceedings.